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# APERTURE LIMITATIONS FOR 2ND GENERATION NB3SN LHC IR QUADRUPOLES[1]

A.V. Zlobin*, V.V. Kashikhin, J.B. Strait, FNAL, Batavia, IL 60510, USA

*Abstract*

One of the straightforward ways towards the higher luminosity in the LHC is a replacement of the present 70-mm NbTi quadrupoles with $Nb_3Sn$ quadrupoles which would provide the same field gradient but in a larger aperture. Conceptual designs of such quadrupoles with 90 mm aperture have been developed and studied. This paper discusses the possibilities and limitations of increasing the aperture of $Nb_3Sn$ low-beta quadrupoles for a LHC luminosity upgrade up to 110 mm.

## INTRODUCTION

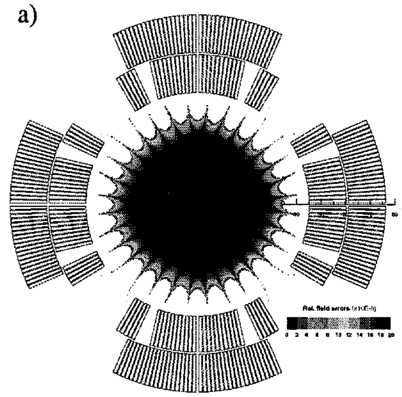
Present optics of two LHC high-luminosity interaction regions (IR) is based on single-bore inner triplets consisting 70-mm NbTi quadrupoles with a nominal field gradient of 205 T/m operating at T=1.9 K. These quadrupole magnets were designed to provide $\beta$*=50 cm at the nominal LHC luminosity of $10^{34}$ $cm^{-2}s^{-1}$ [1]. Replacing these quadrupoles with higher performance magnets will be a major component of the LHC luminosity upgrades.

The future LHC luminosity upgrade plans being discussed at present time require new low-beta quadrupoles with higher field gradient, larger operation margin and larger magnet aperture [2,3]. Preliminary analysis shows that large-aperture quadrupoles based on $Nb_3Sn$ superconductor meet these basic requirements [4,5]. This paper continues the studies with the goal to determine the aperture limitations for $Nb_3Sn$ IR quadrupoles.

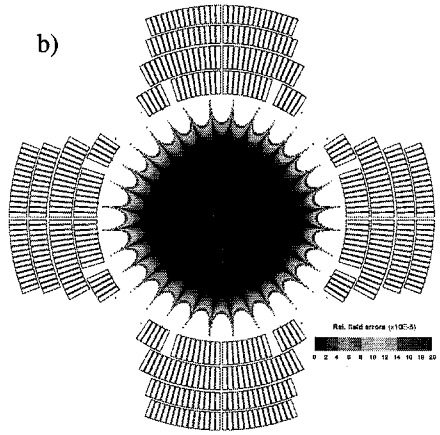
## MAGNET DESIGN

The conceptual design of 90-mm $Nb_3Sn$ quadrupole magnets based on 2-layer shell-type designs has been recently developed and analyzed [6,7]. The 90-mm aperture is close to the limit for a 2-layer design due to the large cable aspect ratio. Therefore 4-layer designs were considered for quadrupoles with 100-mm and 110-mm aperture. Both magnets consist of two double-layer shell-type coils and cold iron yoke. The goal was to achieve a nominal field gradient of 205 T/m with a 20% margin and the best field quality with one wedge in the innermost layer. The current density in the coil layers was graded, providing a noticeable contribution to the field gradients. The circular iron yoke was set 15 mm beyond the coil to provide space for the collars. The magnetic permeability of the iron was constant and equal to 1000. The optimized 4-layer 100 and 110-mm coil cross-sections as well as 2-layer 90-mm quadrupole coil are shown in Figure 1.

a)



b)



c)

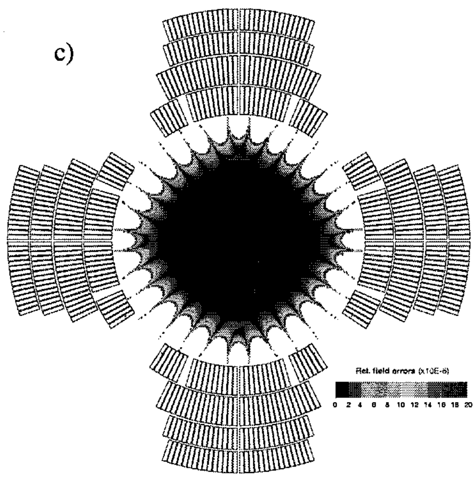


Figure 1: Quadrupole coil cross-sections with 90-mm (a), 100-mm (b) and 110-mm (c) apertures.

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* zlobin@fnal.gov

The coil parameters for all the three quadrupole designs are summarized in Table 1. The coil width and volume required to reach the target field gradient increase dramatically in the 110-mm aperture quadrupole design.

Table 1: Coil parameters.

| Parameter | Aperture | | |
|---|---|---|---|
| | 110 mm | 100 mm | 90 mm |
| Number of layers | 4 | | 2 |
| Number of turns | 248 | 228 | 144 |
| Coil width, mm | 45.5 | 34.5 | 31.5 |
| Coil area, $cm^2$ | 84.9 | 59.3 | 48.1 |

Table 2 summarizes the final cable parameters for the all three designs. Two different cables are used in each 4-layer quadrupoles in order to increase the efficiency of magnet design. The cables are based on the same 1-mm $Nb_3Sn$ strand. The cable dimensions including insulation were determined in an iterative optimization process in order to achieve maximum gradients with minimum coil areas. The cable keystone angle was set to ensure the radial position of each turn in the coil.

The 2-layer 90-mm quadrupole uses the same cable based on the 0.7 mm $Nb_3Sn$ strand in both layers. All cables have the same packing factor of 89% and Cu:nonCu ratio of 1.2. Practical experience shows that the cables used in the 4-layer designs are simpler for manufacturing and have better mechanical and electrical properties than the cable used in the 2-layer design due to the smaller aspect ratio – the ratio of the cable width to the cable thickness.

Table 2: Cable parameters.

| Parameter | Aperture | | | | |
|---|---|---|---|---|---|
| | 110 mm | | 100 mm | | 90 mm |
| Coil layer | 1-2 | 3-4 | 1-2 | 3-4 | 1-2 |
| Number of strands | 24 | 18 | 18 | 14 | 42 |
| Strand D, mm | 1.0 | | | | 0.7 |
| Cable width, mm | 12.33 | 9.23 | 9.23 | 7.17 | 15.14 |
| Inner edge, mm | 1.59 | 1.66 | 1.61 | 1.67 | 1.08 |
| Outer edge, mm | 1.94 | 1.87 | 1.92 | 1.86 | 1.39 |
| Keystone angle, deg | 1.7 | 1.3 | 1.9 | 1.5 | 1.18 |
| Aspect ratio | 7 | 5 | 5 | 4 | 12 |

## MAGNET PARAMETERS

### *Field quality*

Table 3 presents the systematic geometrical harmonics at the reference radius equals to the half of the coil radius for the 100-mm and 110-mm designs and also for the 2-layer 90-mm quadrupole. For comparison the field harmonics of present 70-mm NbTi LHC IR quadrupoles (MQXB) at the reference radius of 17 mm (which as well corresponds to the half bore radius for this magnet) are also presented.

The first allowed geometrical harmonics, $b_6$, at $R_{ref}=R_{bore}/2$ is almost the same for 90-mm quad and 100-mm and 110-mm designs and is noticeably better than in present 70-mm design. The higher order geometrical harmonics, $b_{10}$ and $b_{14}$, are almost the same in 90, 100 and 110 mm designs and slightly higher than in MQXB. If required, the geometrical harmonics can be further optimized by introducing additional wedges in the coil.

Table 3: Systematic field harmonics $b_n$ @$R_{ref}=R_{bore}/2$.

| n | Aperture | | | |
|---|---|---|---|---|
| | 110 mm | 100 mm | 90 mm | 70 mm |
| 6 | 0.0002 | 0.0005 | 0.0006 | -0.013 |
| 10 | 0.0033 | 0.0029 | 0.0045 | -0.001 |
| 14 | 0.0118 | 0.0046 | 0.0069 | -0.0011 |

### *Short sample limit*

Figure 2 shows the calculated quench gradient for 110, 100 and 90 mm quadrupoles as a function of the critical current density in the non-copper area of the superconducting cable. The $Nb_3Sn$ strands with $J_c$(12T,4.2K)>3 kA/mm$^2$ allow a quench gradients above 250 T/m to be reached in all the designs. The R&D program aimed at the development of high $J_c$ $Nb_3Sn$ strands for a new generation SC accelerator magnets has been launched few years ago in the U.S. Based on the results achieved in the framework of this program, the strands with the critical current density >3 kA/mm$^2$ will be available in 2-3 years. Jc(12T,4.2K) of 2.9 kA/mm$^2$ has been reached in short samples, however, more work to be done on reduction of strand magnetization and improvement of their stability.

The data presented in Figure 2 and Table 1 show that the efficiency of the design with larger aperture decreases. In order to reach the same field gradient wider coils with higher critical current density are required.

The maximum field in the coil of the 110, 100 and 90 mm quadrupoles reaches 15.3, 14.5 and 13.5 T respectively. The maximum field in the 110 mm quadrupole exceeds the maximum field achieved in the $Nb_3Sn$ high field accelerator magnets at present time.

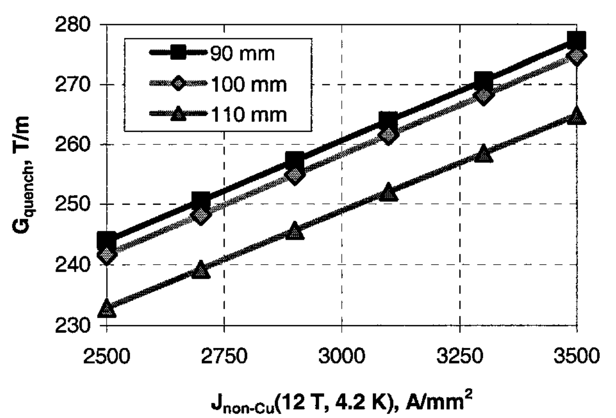


Figure 2: Quench gradients at 4.2 K as functions of the critical current density in the coil.

### *Lorentz forces and coil stress*

Table 4 presents the calculated horizontal and vertical components of the Lorentz force applied to one octant of the coil at the nominal field gradient of 205 T/m, and the maximum stress in the coil associated with these forces. Analysis shows that the level of Lorentz forces in the 90-mm quadrupole reaches the same level as in the LHC arc dipoles. In the quadrupole with 110 mm aperture the expected Lorentz forces are higher than the forces in the $Nb_3Sn$ high field dipole models being developed at the present time for different applications.

The level of mechanical stresses in the coil of 110 mm quadrupole approaches to 100 MPa. To provide the coil pre-stress of this level at operation temperature, the coil prestress during fabrication increases to the level at which significant irreversible $Nb_3Sn$ strand degradation may occur. Clearly, the robust mechanical structure capable of providing an adequate coil support during operation and avoiding coil over-compression during fabrication is a key element for these quadrupole designs.

Table 4: Lorentz forces and maximum coil stress.

| Parameter | Aperture | | |
|---|---|---|---|
| | 110 mm | 100 mm | 90 mm |
| Fx(205T/m), MN/m | 3.44 | 2.38 | 1.5 |
| Fy(205T/m), MN/m | -3.42 | -2.39 | -1.92 |
| Maximum coil stress, MPa | 99 | 90 | 73 |

### *Quench protection*

All superconducting accelerator magnets have large stored energy and require special quench protection system in case of quench. Magnet inductance and stored energy at the nominal field gradient of 205 T/m for the 110, 100 and 90 mm quadrupoles are presented in Table 5. Quench protection of these magnets can be provided using the traditional approach based on internal quench protection heaters which allow distributing the stored energy in the coil, thereby preventing coil overheating and reducing the voltages between the coil and ground as well as mechanical shock in the coil during quench. The acceptable coil maximum temperature for accelerator magnets is 300-400 K. The results of calculation of the maximum coil hot spot temperature, $T_{hs}$, in the region where quench occurred and the maximum temperature under quench heaters, $T_{blk}$, are reported in Table 5 for the fractions of coil volume quenched by the heaters, $F_{qh}$, of 50% and 25%.

Table 5: Quench protection parameters.

| Parameter | | Aperture | | |
|---|---|---|---|---|
| | | 110 mm | 100 mm | 90 mm |
| L, mH/m | | 17.46 | 14.71 | 4.86 |
| W(205 T/m), kJ/m | | 1181 | 703 | 468 |
| $T_{hs}$, K | $F_{qh}$=50% | 230 | 225 | 230 |
| | $F_{qh}$=25% | 335 | 320 | 315 |
| $T_{blk}$, K | $F_{qh}$=50% | 150 | 140 | 127 |
| | $F_{qh}$=25% | 220 | 200 | 180 |

For the redundancy of quench protection system the $F_{qh}$ should be less than 50%. In this case two parallel sets of heaters could be installed in the magnet. Calculations show that even for $F_{qh}$=25% the coil maximum temperature in all the quadrupole designs is within 315-335 K. With $F_{qh}$=50% the maximum temperature does not exceed 250 K which is acceptable for brittle $Nb_3Sn$ coils.

## CONCLUSION

The studies presented here show that a 110-mm aperture quadrupole magnet using $Nb_3Sn$ strand can provide the maximum field gradient of 250 T/m (20% above the present nominal gradient of 205 T/m) with acceptable field quality. Quench protection of these magnets can be provided using the traditional approach based on internal quench heaters.

Single-aperture inner triplets with these magnets can reduce $\beta^*$ by a factor of 3, from 50 cm to 17 cm leading to a potencial luminosity increase by a factor of 3.

However, the following parameters make the 110 mm quadrupoles quite challenging:

- the critical current margin of 20% requires high-performance $Nb_3Sn$ strands with the critical current density Jc(12T,4.2K)>3 kA/mm$^2$;
- the peak field in the coil at quench exceeds the state-of-the-art level of 15 T for $Nb_3Sn$ accelerator magnets;
- the Lorentz forces in the coils are large so that the maximum coil stress reaches 100 MPa approaching to the level of stresses which may cause degradation or even damage of brittle $Nb_3Sn$ coils.

The risks associated with the above factors have to be analyzed and taken into account while choosing the final quadrupole aperture.

## REFERENCES


[1] "The Large Hadron Collider" Conceptual Design, CERN/AC/95-05 (LHC), 20 October 1995.

[2] T. Taylor, "Superconducting Magnets for a Super LHC", EPAC 2002, Paris, France, p.129.

[3] O. Brüning, et al., "Towards a New LHC Interaction Region Design for a Luminosity Upgrade", presented at PAC 2003, Portland, OR, May 2003.

[4] T. Sen, J. Strait, A.V. Zlobin, "Second Generation High Gradient Quadrupoles for the LHC Interaction Regions", PAC 2001, Chicago, IL, June 2001, p.3421.

[5] T. Sen et al., "Beam physics issues for a possible 2nd generation LHC IR", EPAC2002, Paris (France), June 2002, p.371.

[6] A.V. Zlobin et al, "Large-Aperture $Nb_3Sn$ Quadrupoles for 2nd generation LHC IRs", EPAC2002, Paris (France), June 2002, p.2451.

[7] A.V. Zlobin et al., "Conceptual design study of $Nb_3Sn$ low-beta quadrupoles for 2nd generation LHC IRs", Proceedings of 2002 Applied Superconductivity Conference, Houston, TX, August 2002.